

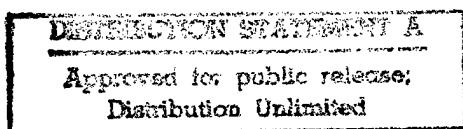


A Preliminary Study on the Vapor/Mist Phase Lubrication of a Spur Gearbox

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A PRELIMINARY STUDY ON THE VAPOR/MIST PHASE LUBRICATION OF A SPUR GEARBOX

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SUMMARY

Organophosphates have been the primary compounds used in vapor/mist phase lubrication studies involving ferrous bearing material. Experimental results have indicated that the initial formation of an iron phosphate film on a rubbing ferrous surface, followed by the growth (by cationic diffusion) of a lubricious pyrophosphate-type coating over the iron phosphate, is the reason organophosphates work well as vapor/mist phase lubricants. Recent work, however, has shown that this mechanism leads to the depletion of surface iron atoms and to eventual lubrication failure. A new organophosphate formulation was developed which circumvents surface iron depletion. This formulation was tested by generating an iron phosphate coating on an aluminum surface. The new formulation was then used to vapor/mist phase lubricate a spur gearbox in a preliminary study.

INTRODUCTION

Klaus, Lai, and Graham (refs. 1 and 2), laid the foundation for high temperature vapor phase lubrication studies when they used tributyl phosphate (TBP) and tricresyl phosphate (TCP) vapors, delivered in a carrier gas, to form deposit films on metal surfaces and to lubricate a four-ball wear tester. Since then, a number of vapor phase lubrication studies, using organophosphates, have been reported. Vapor phase lubrication research can be divided into deposition studies and dynamic friction and wear studies.

In deposition studies, organophosphate molecules are impinged at hot metal or ceramic surfaces and subsequent surface reactions are analyzed. The results from these deposition studies indicated that lubricating films formed only on metal surfaces containing certain active metal sites such as iron or copper (ref. 3). Lubricating films did not form on SiC (ref. 4), nickel (ref. 3) or aluminum (ref. 5) surfaces.

Dynamic friction and wear studies have been conducted using a four ball wear tester (ref. 2), a pure sliding reciprocating tester (ref. 6), a ball-on-rod tester (ref. 7) and a gas turbine engine (ref. 8). In general, successful results were reported for vapor phase lubrication of ferrous material such as cast iron, M50 steel, and 1018 steel specimens. Vapor phase lubrication of ceramics and a Ni-based superalloy were unsuccessful. The work conducted by Forster et al. (ref. 8) also revealed that lubricant delivery as a mist to rubbing surfaces worked as well as vapor delivery, prompting the phrase "vapor/mist phase lubrication."

The experimental results indicate organophosphates work well with certain ferrous materials due to an initial, rapid formation of a predominant iron phosphate film. This is followed by the formation and growth of a pyrophosphate-type film over the iron phosphate via cationic diffusion. As long as iron is present at a wearing surface the vapor phase lubrication method using organophosphates works well. Evidence, however, has been reported (ref. 9) that continued organophosphate interaction with ferrous bearing materials can lead to depletion of surface iron and to eventual lubrication failure.

If vapor/mist phase lubrication is to work for prolonged periods of time then the depletion of surface iron must be circumvented. A deposition study was undertaken to test the capability of a new organophosphate solution,

containing an iron additive, to form iron phosphate on the surface of aluminum reasoning that if an iron phosphate film can be formed on an aluminum surface then it may be formed on most other surfaces. A preliminary dynamic test was then undertaken testing the new organophosphate solution, as a vapor/mist phase lubricant, in a spur gearbox.

EXPERIMENTAL

Deposition Studies

An alcohol solution was prepared by dissolving 1 g of an aryl phosphate ester into 100 ml of ethanol. A second solution was prepared by dissolving 1 g of the same phosphate ester, and 1 gram of ferric acetylacetone into 100 ml of ethanol (ref. 10). Aluminum foil samples (1×1 cm) were ultrasonically cleaned in an acetone bath for 10 min and dried in air. One foil sample was dipped into the phosphate/ethanol solution for 1 min, withdrawn from the solution and the ethanol allowed to evaporate from the foil surface. The foil was then inserted into a preheated oven (300°C) for 2 min. This procedure was repeated for a second foil sample dipped into the phosphate/ferric acetylacetone/ethanol solution. The foil samples were analyzed using X-ray photoelectron spectroscopy (XPS). The XPS spectra were acquired on a commercial spectrometer operated at 100 eV pass energy. The sample surface was perpendicular to the spectrometer axis, the spectrometer acceptance angle was ± 12 degrees, and the area of analysis was 2×5 mm. Non-monochromatized, Al K-alpha x-rays were used. The areas of peaks in the spectra were calculated by subtracting a Shirley background, and the composition of the specimen surface was calculated from the areas by applying sensitivity factors supplied by the instrument manufacturer. Depth profiling of surface films was not attempted in this study.

Spur Gear Test Facility

The facility (ref. 11) used to conduct the vapor/mist phase lubrication tests is shown in figure 1. It operates in a closed-loop arrangement where the drive motor only needs to supply the power to overcome the frictional losses of the system. The system loop is loaded through a torque actuator contained internal to one of the slave gears. High pressure oil, the same oil used to lubricate the gears under normal operation, is supplied to the rotating shaft via a seal assembly. The level of pressure applied to the torque actuator is related to the level of contact stress attained.

The test gears are aligned such that only one half of the face width is loaded. Using the test hardware in this manner can permit four fatigue tests to be run on one pair of gears provided tooth breakage does not occur. The facility can operate with the gears transmitting 75 kW (100 hp) at rotational speeds equal to 10 000 rpm. These maximum test rig conditions will induce a Hertzian contact stress maximum of 1.7 GPa. The test gears were made from AISI 9310 gear steel. Test gear dimensional information is contained in table I.

The existing spur gearbox was modified to accommodate a misting unit (fig. 2a). A photograph of the test arrangement is shown in figure 2(b). The mister was filled with the aryl phosphate ester and compressed air was used to deliver the ester to the spur gearbox as a fine mist or fog. The spur gears were then rotated initially at 2400 rpm and 0.5 GPa contact stress for 5 min. The gearbox was then disassembled and the gears removed and cleaned for visual inspection. After inspection, the gears were assembled back in the gearbox and rotated at a higher speed and load for another five minutes before stopping the test run for another visual inspection. This procedure was repeated several more times until a final run was made at 7000 rpm at 1.1 GPa contact stress.

A 1 percent (by weight) solution of ferric acetylacetone in the phosphate ester was prepared and loaded into the mister unit. Subsequent lubrication tests were performed using different sets of gears, again gradually increasing the gear speed and load capacity. The gearbox was modified to allow insertion of a thermocouple to monitor the turbulent air temperature next to one of the gears (fig. 3).

RESULTS AND DISCUSSION

Deposition Studies

Figure 4 is the XPS spectrum of the heat-treated Al surface which was dipped into the pure phosphate solution. Oxygen, carbon, and aluminum peaks were identified but not phosphorous. The calculated aluminum-to-oxygen

ratio, from the XPS spectrum, is 0.60 and the stoichiometric aluminum-to-oxygen ratio for aluminum oxide, Al_2O_3 , is 0.66. Comparison of these two ratios, along with the XPS spectrum, indicates an aluminum oxide surface with carbonaceous material over it.

Figure 5 is the XPS spectrum for the heat treated Al surface which was dipped into the ferric/phosphate solution. Oxygen, carbon, iron and phosphorus peaks were detected but not aluminum. This indicates the presence of a film thick enough to cover the strongly absorbing aluminum on the foil surface. If only iron phosphate is present then the phosphorous-to-iron and the phosphorous-to-oxygen ratios, from the XPS spectrum, should be about 1 and 0.25 respectively. The ratios, however, are 0.55 and 0.19 which indicates excess iron and oxygen. This excess iron and oxygen could be present as iron oxide but further surface analysis is needed to discern the calculated ratios. Nevertheless, the XPS spectrum indicates a phosphate film, with carbonaceous material, covering the aluminum surface.

This deposition study revealed the inability of a phosphate film to form on an aluminum surface using only the pure organophosphate. Either the organophosphate simply evaporated from the surface or it decomposed with subsequent evaporation of the decomposition products. This result is not surprising considering a review of phosphate conversion coatings in the literature (ref. 12). In general, cast irons and low carbon steels are easily phosphated whereas stainless steels cannot be successfully phosphate coated. The only phosphate easily deposited on aluminum surfaces is zinc phosphate and only via a process where fluoride ions are present in a phosphating bath. This study, however, has shown that the presence of ferric acetylacetone, in the organophosphate, led to the formation of an iron phosphate film on the aluminum foil. The iron phosphate film on any metal or ceramic surface is crucial for successful high temperature, vapor/mist phase lubrication.

Spur Gear Studies

The results of the first test, using only pure phosphate ester, are summarized in table II. This run was conducted in 5 min intervals where, at the end of each interval, the gears were disassembled and visibly examined. No tooth wear or scratches were observed at the end of the first interval. The speed and load were increased for the second interval. This time slight scratches on some of the teeth were observed. The speed and load were increased for the third and fourth intervals with no visible changes to the gear teeth. At the end of the fifth interval, surface scratches on the gear teeth were more pronounced. No changes were noticed for the sixth interval. For the seventh interval, a 1.1 GPa contact stress was applied to the gears rotating at 7000 rpm. Two minutes elapsed before a sudden increase in noise was heard and the test stopped. The test chamber was very cloudy as seen through the plexiglass window covering the test gears. Visual inspection revealed 3 teeth on the driver gear and 9 teeth on the driven gear had severely overheated as noted by the bluish discoloration of the teeth (ref. 13).

The driver gear was continuously sprayed with ethanol for several minutes to remove residual oil. One gear tooth, randomly selected, was removed and its contact surface analyzed using XPS. Its XPS spectrum, shown in figure 6, revealed a surface film consisting essentially of carbon and oxygen. A small iron peak was detected along with a few minor contaminants. No phosphorous was detected.

Because only three sets of spur gears were available for experimentation, it was decided to mist phase lubricate a new set with the 1 percent ferric/phosphate solution. A thermocouple recorded the fling-off air lubricant temperature near the driven gear. The results of this second test are summarized in table III. The run started with a gear rotation of 2800 rpm, no load on the gears, and an initial temperature of 20 °C. Gear speed or load was increased every 5 min; however, this time the gearbox was stopped for gear inspection only at the end of the sixth interval. The thermocouple measured 38 °C at the end of the first interval. The gear load pressure was increased to apply a contact stress equal to 0.8 GPa for the second interval and a 50 °C temperature reading was recorded. During the next three intervals, the speed and load were increased to 7300 rpm and 1.1 GPa contact stress. The temperature increased to 84 °C.

Inspection of the gear teeth at the end of the sixth interval revealed only slight wear scars on the teeth. After reassembly, the gearbox was started at 7730 rpm and a 1.3 GPa contact stress was applied. This seventh interval ran for 10 min and the thermocouple held steady at 92 °C. The load was increased to 1.5 GPa contact stress for the eighth interval where the gearbox ran for 1.5 min until a sudden increase in gear noise and vibration resulted in test termination. The temperature increased rapidly to 119 °C. Inspection of the gears showed worn teeth but no fatal damage and the gear teeth were not discolored.

Table IV summarizes the results of the third test, again using the 1 percent ferric/organophosphate solution, where the position of one of the air/mist jets was changed (fig. 7) to lubricate the gear teeth just before they entered

the contact zone. This run started with a gear speed of 3000 rpm and 0.8 GPa contact stress. The thermocouple measured 32 °C after the first (5 min) interval. The speed was increased to 7000 rpm for the second interval and the temperature reached 57 °C. The load was increased to 1.1 GPa contact stress for the third interval where the temperature rose to 72 °C. The load was increased to 1.3 GPa for the fourth interval where the temperature rose to 85 °C. The gear speed was increased to 10 000 rpm for the fifth interval where the temperature gradually rose to 149 °C and then started to decrease. During the next 7 min, the sixth interval, the temperature dropped and stabilized at 141 °C. The load was increased to 1.4 GPa for the seventh interval. The temperature increased steadily to 164 °C when the test was terminated. Gear teeth examination revealed some visible wear but very little surface metal removal, and no discoloration of the teeth was observed.

After ethanol cleaning, a tooth from the driver gear was removed and its contact surface analyzed using XPS. The XPS spectrum (fig. 8) revealed a surface film consisting primarily of carbon and oxygen along with amounts of iron and phosphorus. Minor contaminants were also present.

Unfortunately only three gear runs could be performed at this time. It was deemed, however, that these favorable results justified a preliminary report. Keeping in mind that we were lubricating the spur gears with about 0.1 percent of the oil capacity used during normal operation, no catastrophic wear of the gear teeth occurred. The major differences between the runs were: (1) the blue discoloration of several gear teeth, which occurred only for the pure organophosphate run, indicating very high gear temperatures, and (2) the presence of iron and phosphorous on the gear tooth surface, from the last run, using the iron additive.

Although much work remains to be done—for instance, optimizing the concentration of the iron additive in the organophosphate, adjusting the flow rates, selecting the best locations for the mist jets—this method can be used immediately as an emergency back-up system for helicopter transmission gearboxes in the event of oil loss. One or two liters of the ferric/organophosphate solution can be used as a vapor/mist phase lubricant allowing the pilot ample time to safely land his craft.

CONCLUSIONS

Deposition studies, using a pure aryl organophosphate on aluminum foil, revealed that a phosphate film did not form on the foil surface. An iron phosphate film, however, did form on the foil surface using a ferric acetylacetone/organophosphate solution. This unique liquid solution provides the means to circumvent iron depletion on ferrous surfaces vapor/mist phase lubricated with organophosphates. It also ensures successful vapor/mist phase lubrication on nonferrous surfaces. A minute amount of this formulation was used to successfully lubricate a spur gearbox at high speed and load.

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TABLE I.—SPUR GEAR DATA

[Gear tolerance per AGMA class 12.]

| | |
|--|-----------------|
| Number of teeth | 28 |
| Diametral pitch | 8 |
| Circular pitch, cm (in.) | 0.9975 (0.3927) |
| Whole depth, cm (in.) | 0.762 (0.300) |
| Addendum, cm (in.) | 0.318 (0.125) |
| Chordal tooth thickness (reference), cm (in.) | 0.485 (0.191) |
| Pressure angle, deg | 20 |
| Pitch diameter, cm (in.) | 8.890 (3.500) |
| Outside diameter, cm (in.) | 9.525 (3.750) |

TABLE II.—SPUR GEARBOX TEST USING PURE ORGANOPHOSPHATE

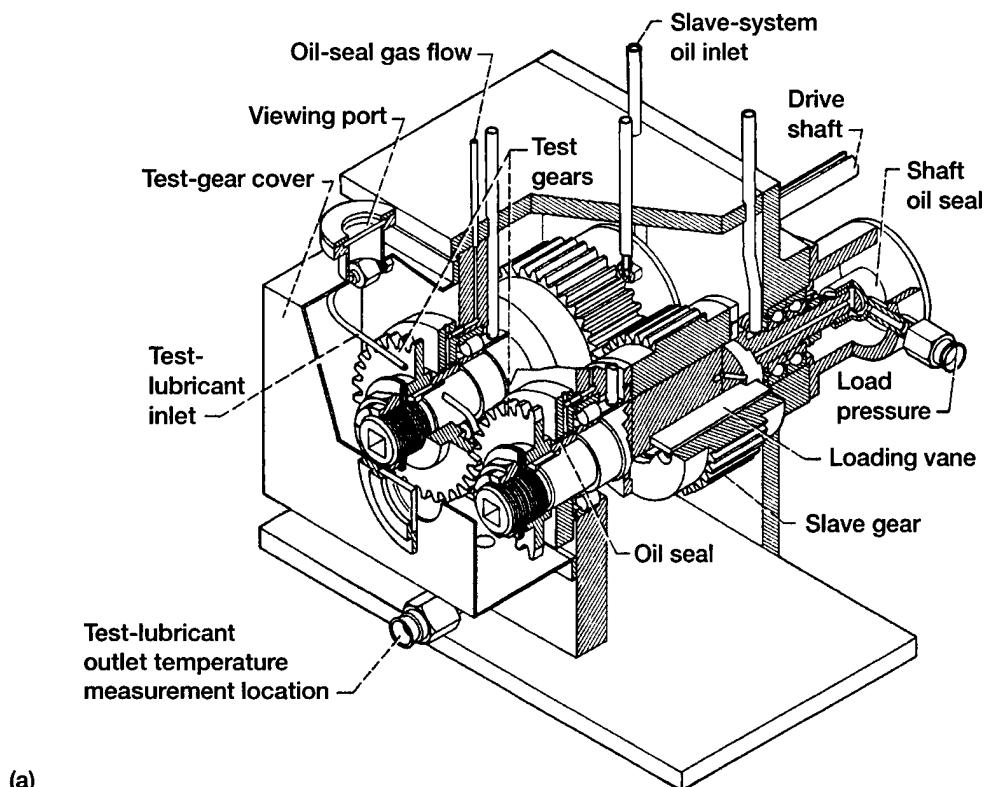
| Interval | Elapsed test time, min during interval | RPM | Gear contact stress, GPa | Observation |
|----------|--|------|--------------------------|----------------------------|
| 1 | 0 to 5 | 2400 | 0.5 | No visible wear |
| 2 | 5 to 10 | 2700 | 0.8 | Slight scratches on teeth |
| 3 | 10 to 15 | 2830 | 0.8 | No change |
| 4 | 15 to 20 | 4900 | 0.8 | No change |
| 5 | 20 to 25 | 4900 | 0.9 | Surface scratches on teeth |
| 6 | 25 to 30 | 7000 | 0.9 | No change |
| 7 | 30 to 32 | 7000 | 1.1 | Shut down |

TABLE III.—SPUR GEARBOX TEST USING 1 PERCENT FERRIC/PHOSPHATE FORMULATION

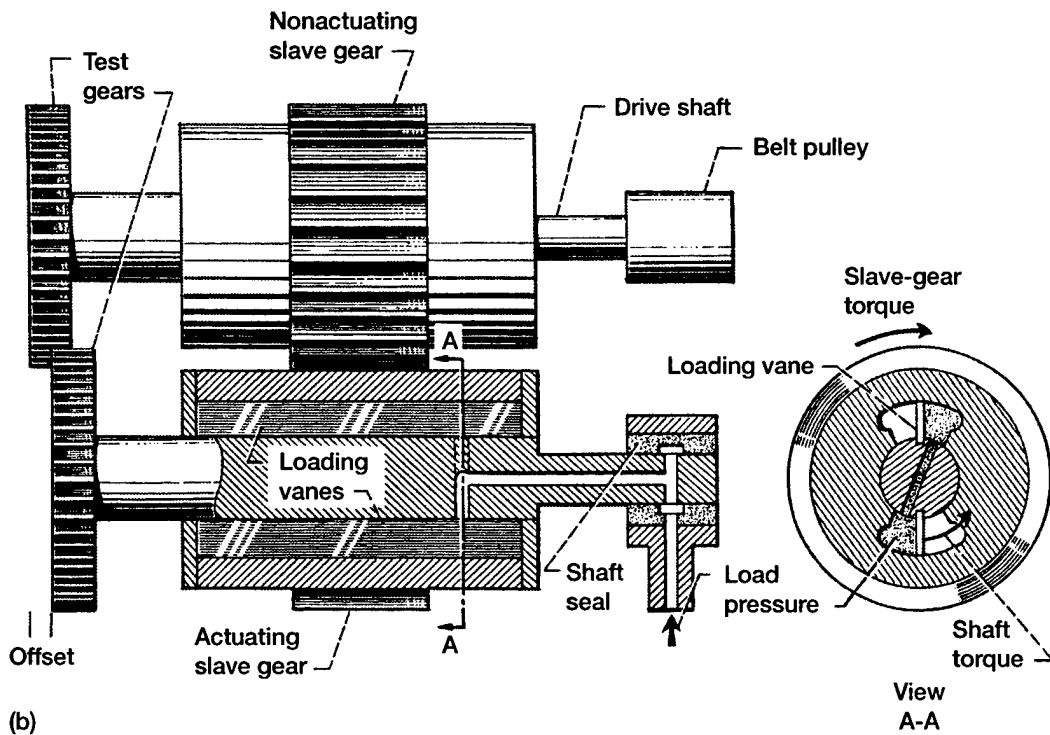
| Interval | Elapsed test time, min during interval | RPM | Gear contact stress, GPa | Temperature, °C |
|----------|--|------|--------------------------|-----------------|
| 1 | 0 to 5 | 2800 | 0 | 38 |
| 2 | 5 to 10 | 2800 | 0.8 | 50 |
| 3 | 10 to 15 | 4200 | 0.8 | 59 |
| 4 | 15 to 20 | 4200 | 1.1 | 67 |
| 5 | 20 to 25 | 7300 | 1.1 | 84 |
| 6 | 25 to 30 | 7300 | 1.3 | 91 |
| 7 | 30 to 40 | 7730 | 1.3 | 92 |
| 8 | 40 to 41.5 | 7730 | 1.5 | 119 |

TABLE IV.—SPUR GEARBOX TEST USING 1 PERCENT FERRIC/PHOSPHATE FORMULATION WITH DIFFERENT JET PLACEMENT

| Interval | Elapsed test time, min during interval | RPM | Gear contact stress, GPa | Temperature, °C |
|----------|--|--------|--------------------------|-----------------|
| 1 | 0 to 5 | 3000 | 0.8 | 32 |
| 2 | 5 to 10 | 7000 | 0.8 | 57 |
| 3 | 10 to 15 | 7000 | 1.1 | 72 |
| 4 | 15 to 20 | 7000 | 1.3 | 85 |
| 5 | 20 to 25 | 10 000 | 1.3 | 149 |
| 6 | 25 to 32 | 10 000 | 1.3 | 141 |
| 7 | 32 to 37 | 10 000 | 1.4 | 164 |



(a)



(b)

Figure 1.—NASA Lewis Research Center's gear fatigue test apparatus. (a) Cutaway view. (b) Schematic diagram.

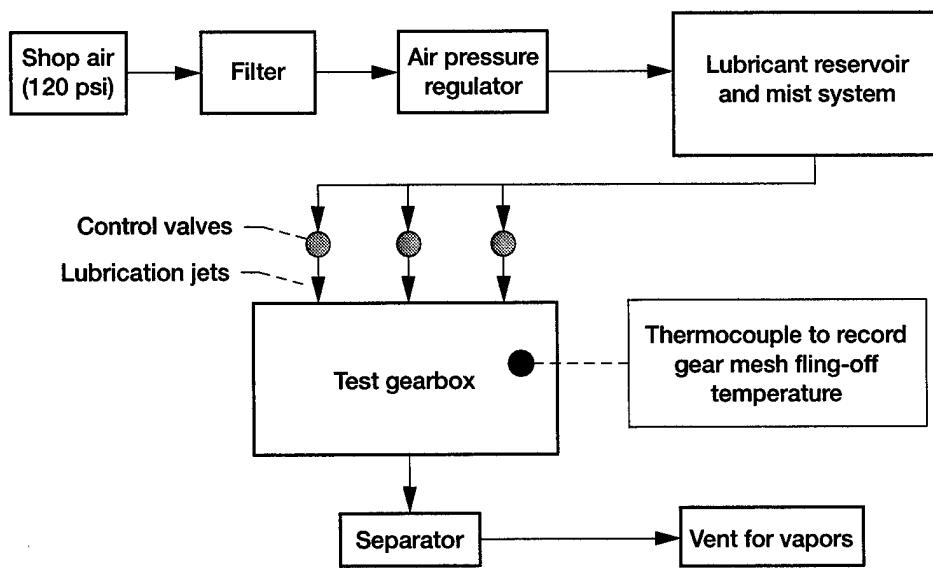


Figure 2a.—Vapor/mist phase lubrication system.

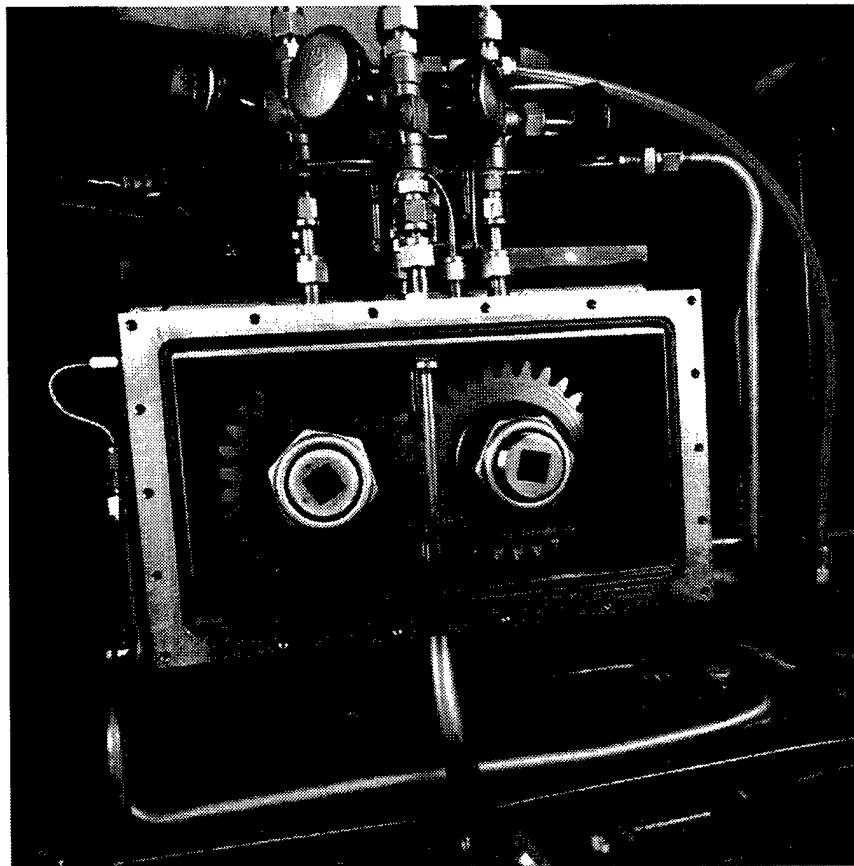


Figure 2b.—Photograph of experimental test arrangement.

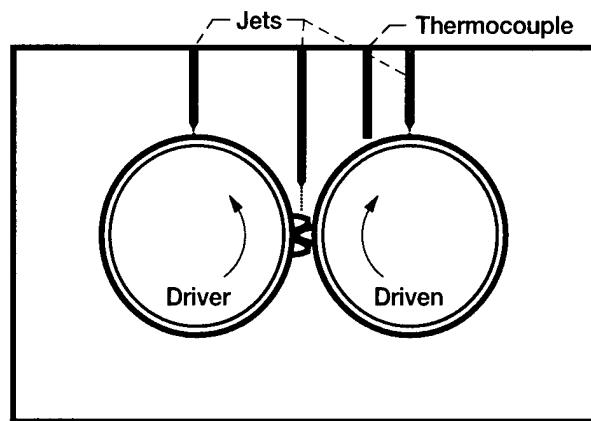


Figure 3.—Spur gearbox showing jet and thermocouple placement. Each gear has twenty eight teeth, only a select few shown here.

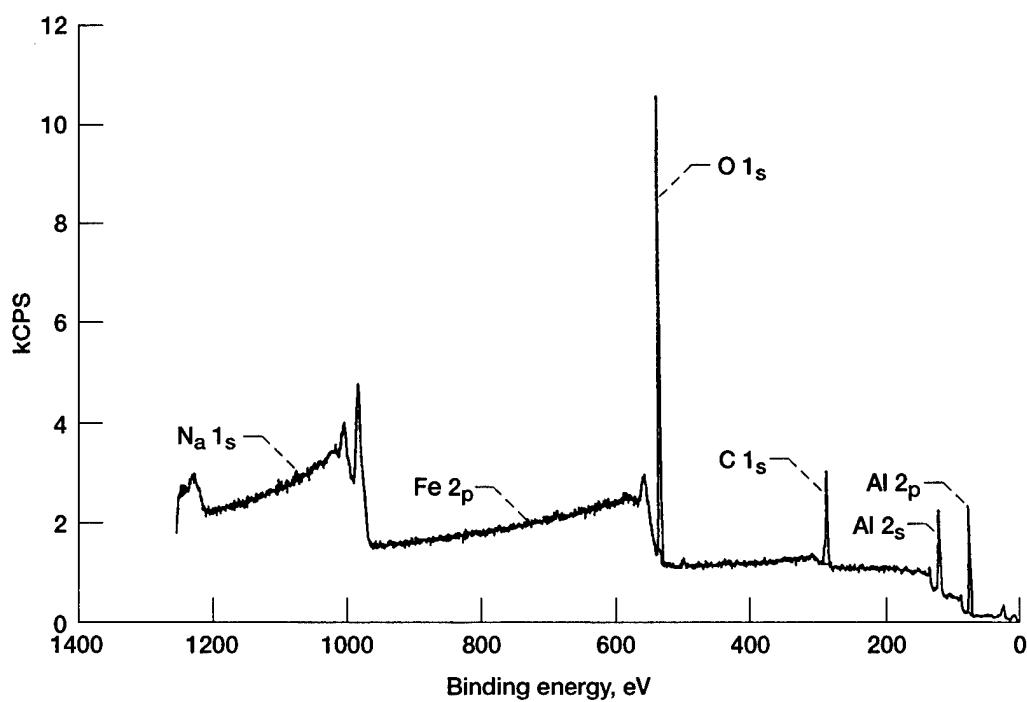


Figure 4.—XPS spectrum of heat-treated Al surface dipped into pure phosphate solution.

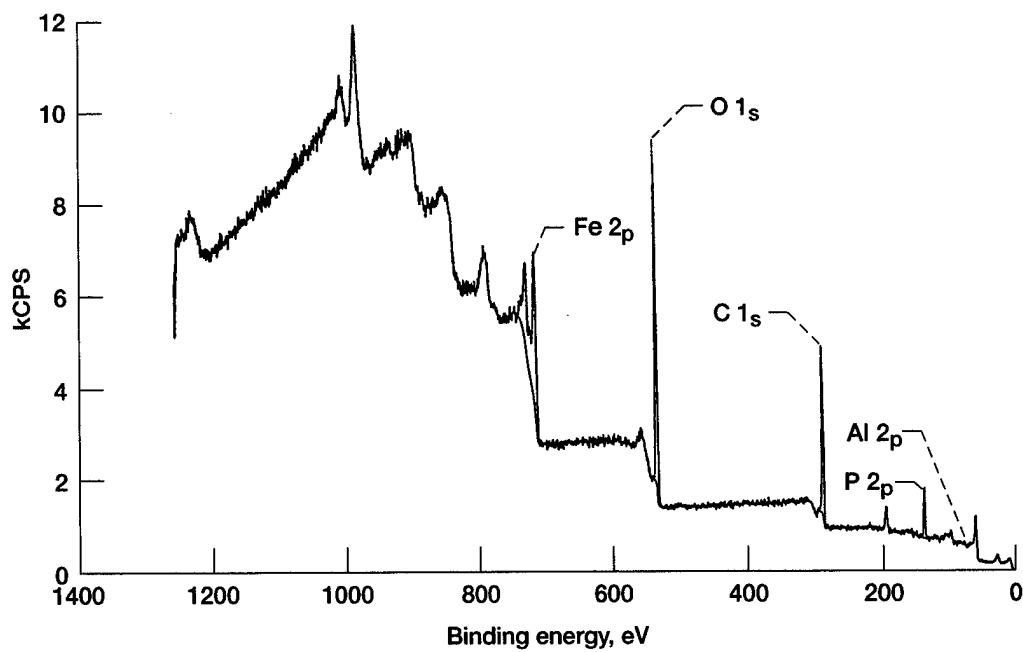


Figure 5.—XPS spectrum of heat-treated Al surface dipped into ferric/phosphate solution.

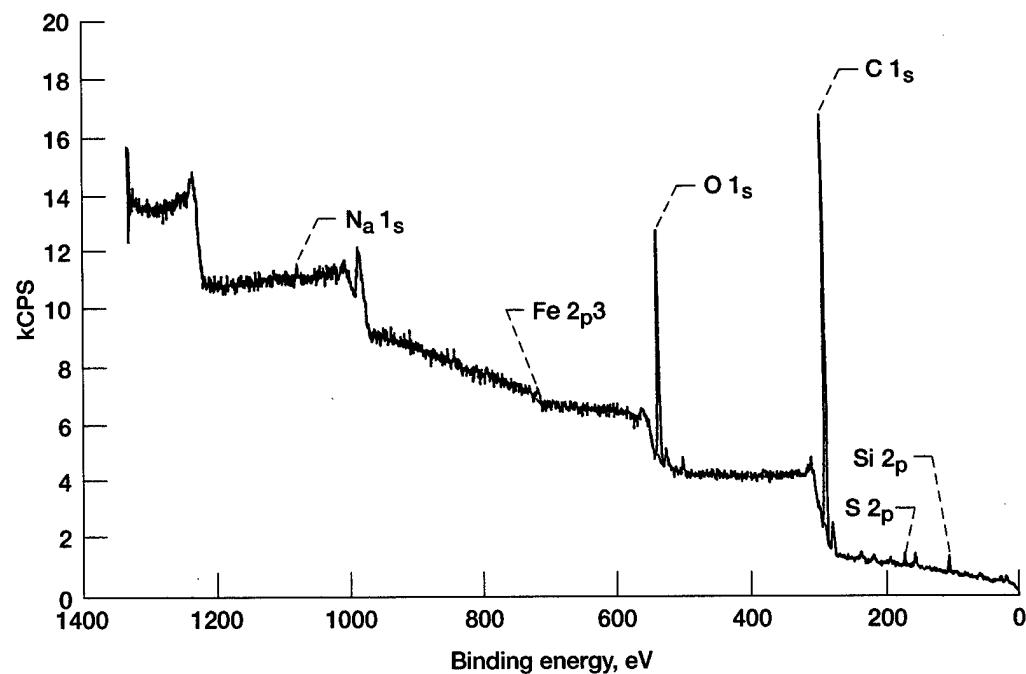


Figure 6.—XPS spectrum of gear tooth from test conducted using pure phosphate.

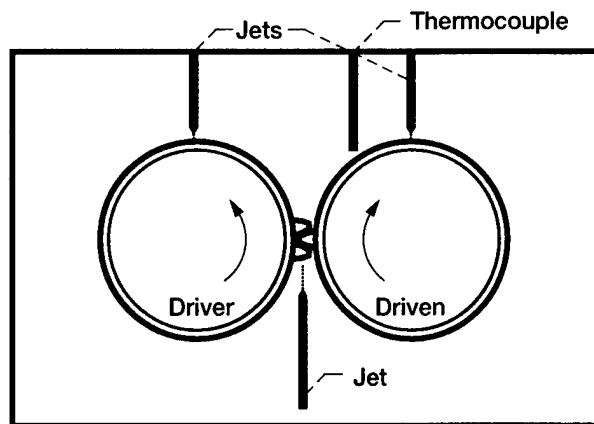


Figure 7.—Spur gearbox showing different jet placement.

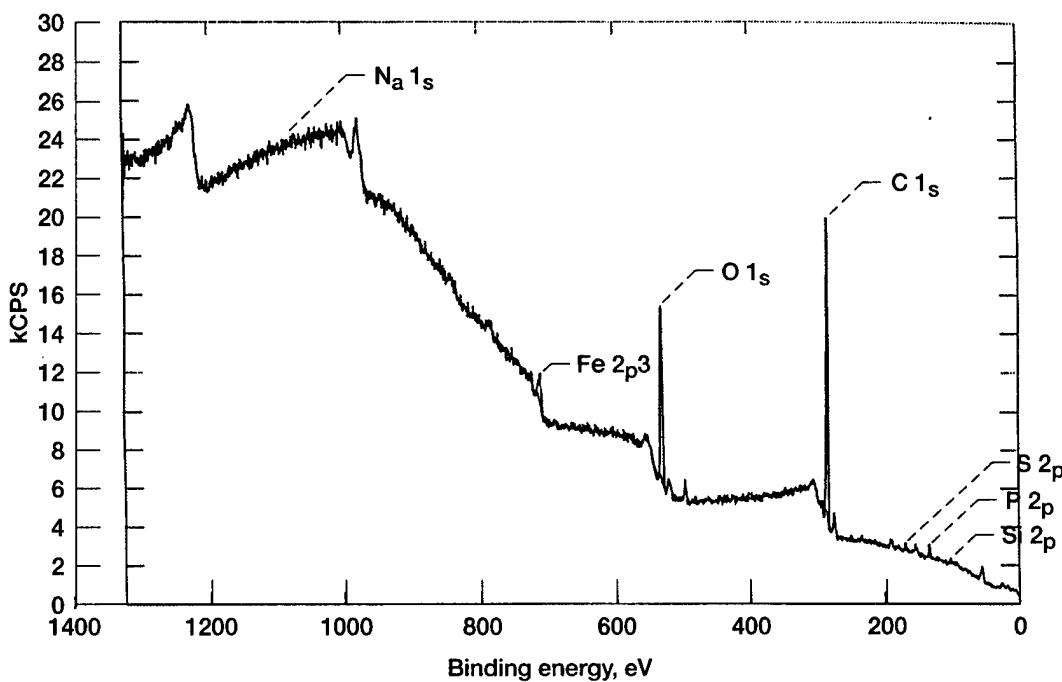


Figure 8.—XPS spectrum of gear tooth from test conducted using the ferric/phosphate formulation.

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